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Low-energy line emission from Cygnus X-2 observed with the *BeppoSAX* LECS

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Abstract. We present a 0.2–10 keV spectrum of the low-mass X-ray binary Cygnus X-2 obtained using the Low Energy Concentrator Spectrometer on-board *BeppoSAX*. The spectrum can be described by a cut-off power-law model with absorption of $(2.28\pm0.07)\times10^{21}$ atoms cm^{-2}, a power-law index of 0.78 ± 0.02 and a cut-off energy of 4.30 ± 0.08 keV (68% confidence errors), except at energies near $\sim$1 keV where excess emission is present. This can be modeled by a broad Gaussian line feature with an energy of 1.02 ± 0.04 keV, a full width half-maximum of 0.47 ± 0.07 keV and an equivalent width of $74\pm^{25}_{11}$ eV. This result confirms earlier reports of line emission near 1 keV and shows the intensity and structure of the feature to be variable.

Key words: accretion – binaries:close – stars:individual (Cyg X-2) – stars:neutron – X-rays: general

1. Introduction

Cygnus X-2 is a bright persistent low-mass X-ray binary (LMXRB), whose X-ray spectrum has been studied from $\sim$0.1 to several hundred keV. Together with some of the other bright persistent LMXRB sources it is classified as a "Z" source (Hasinger & van der Klis 1989). The changes in the X-ray spectral shape of Z sources are subtle, but in an X-ray color-color diagram the sources trace out Z-like shaped patterns. They move through the Z in a smooth manner without jumping from branch to branch. Z sources are thought to be accreting material at near-Eddington rates via an accretion disk onto a neutron star (e.g. Hasinger et al. 1990).

The Italian-Dutch satellite *BeppoSAX* is the first mission to simultaneously observe in the 0.1–300 keV energy range using a complementary payload of instruments (Boella et al. 1997). The Low-Energy Concentrator Spectrometer (LECS) is sensitive in the energy range 0.1–10 keV (Parmar et al. 1997). Its unique design utilizes a driftless gas scintillation proportional counter to make the lowest energies accessible with a good energy resolution while providing 16 μs time resolution and moderate spatial resolution. The LECS has a circular field of view of 37′ diameter and a 0.1–10 keV background counting rate of 9.7×10^{-5} arcmin^{-2} s^{-1}. The LECS energy resolution, ΔE/E, is 19% at 1 keV and varies as E$^{-0.42}$. In this *Letter* results from the LECS are presented for one of the Science Verification Phase targets, Cyg X-2. We find that the 0.2–10 keV spectrum can be described by an absorbed cut-off power-law model, with additional emission at energies near $\sim$1 keV.

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2. Observation and Results

BeppoSAX observed Cyg X-2 between 1996 July 23 00:19 and 18:18 UTC. Good data were selected from intervals when the minimum elevation angle above the Earth's limb was >4° and when the instrument configuration was nominal using the SAXLEDAS 1.4.0 data analysis package (Lammers 1997). The LECS was only operated during satellite night-time giving a total on-source exposure of 7.1 ks. A spectrum was extracted centered on the mean source position using the standard LECS extraction radius of 8′ and the appropriate response matrix was generated. Background subtraction was performed using a standard blank field 46 ks exposure, but is not critical for such a bright source. The spectrum was rebinned to have at least 20 counts per channel. Channels below 0.2 keV were discarded since the source is absorbed below this energy. The mean LECS count rate observed from Cyg X-2 is 67 s^{-1}, which corresponds to an observed 1–10 keV flux of 7.4×10^{-9} erg cm^{-2} s^{-1}.

The ground calibration of the LECS is discussed in Parmar et al. (1997). The effective area $\lesssim$2 keV is primarily limited by the entrance window transmission, and at higher energies by the loss of reflectivity of the mirror

Table 1. Fit results to the LECS Cyg X-2 spectrum[a]

	Model		
	Cut-off power-law	Cut-off power-law + Gaussian	Units
N_H	2.22 ± 0.04	2.28 ± 0.07	10^{21} H atoms cm^{-2}
γ	0.876 ± 0.012	0.774 ± 0.019	
E_{cut}	4.77 ± 0.09	4.30 ± 0.08	keV
K	1.267 ± 0.008	1.220 ± 0.011	photons cm^{-2} s^{-1} keV^{-1} at 1 keV
E_c		1.02 ± 0.04	keV
FWHM		0.47 ± 0.07	keV
EW		$74\pm^{25}_{11}$	eV
χ^2_ν/dof	1.45/925	1.20/922	

[a] Uncertainties are given at the 68% confidence level.

system. Great care was taken to determine the entrance window transmission using monochromatic X-ray sources (Bavdaz et al. 1994). The LECS spectral response was updated following the first *BeppoSAX* observation of the Crab Nebula on 1996 September 6. When the LECS spectrum is fit by an absorbed power-law model, the individual energy channel residuals are $\lesssim$5%. The calibration status of the *BeppoSAX* instruments, derived from the above observation, is discussed in Cusumano et al. (1997).

The Cyg X-2 spectrum can be modeled by a cut-off power-law ($KE^{-\gamma}\exp(E_{cut}/kT)$) together with low energy absorption, N_H, which gives a χ^2_ν of 1.45 for 925 degrees of freedom (dof), see also Table 1. Examination of the residuals shows excess counts near 1 keV which are unlikely to originate from calibration uncertainties or other instrumental effects. These excess counts can be modeled by a blackbody of temperature 0.181±0.007 keV giving a χ^2_ν of 1.25 for 923 dof. However, previous observations of Cyg X-2 have required much higher blackbody temperatures of 1.0–1.5 keV (e.g. Hasinger et al. 1990), and it is therefore unlikely that this feature is the blackbody previously observed from the source. Replacing the blackbody with a broad Gaussian line feature with an energy, E_c, of 1.02 ± 0.04 keV, a full width at half-maximum, FWHM, of 0.47±0.07 keV and an equivalent width, EW, of $(74\pm^{25}_{11})$ eV in the fit gives a better fit with a χ^2_ν of 1.20 for 922 dof. An *F*-test indicates that this difference is significant, but only at the 1σ level. Higher energy resolution Cyg X-2 observations than that reported here (e.g. using the *Einstein* Objective Grating Spectrometer (OGS); see Vrtilek et al. 1988), require the presence of multiple line features near 1 keV. This supports the interpretation of the excess emission seen in the LECS as unresolved line emission. Table 1 gives the best-fit parameters for the Gaussian line model. Fig. 1 shows the observed count spectrum and the best-fit model when the normalization of the emission feature is set to zero.

In addition to the feature at ~1 keV, there is evidence for weak narrow-line features at 1.54±0.03, 2.01±0.02, and 2.61±0.02 keV in the LECS spectrum (see Fig. 1). Including all three lines in the fit reduces the χ^2_ν to 1.15 for 916 dof. The energies of two of these lines are consistent with Lyα transitions of H-like Si XIV and S XVI at 2.00 and 2.62 keV, respectively (see e.g. Raymond 1993). However, we caution that these features have energies close to those of the mirror Au edges, where the LECS calibration is more uncertain. There is no evidence for Gaussian line emission near 6.7 keV, with a 3σ upper limit on the equivalent width of 62 eV for a narrow line.

Vrtilek et al. (1988) have compiled the results of *Einstein* OGS and medium-resolution Solid State Spectrometer (SSS) observations of Cyg X-2. The OGS data indicate the presence of four narrow emission lines between 0.74 and 1.12 keV (see Table 2). If the lower resolution SSS data is fit with the same set of line energies, the results are broadly consistent with the OGS results except that the EW of each of the lines is a factor ~2 larger (Vrtilek et al. 1988). In order to investigate whether the excess emission seen by the LECS is consistent with the same blend of lines as seen by *Einstein*, the broad Gaussian emission feature was replaced by four narrow lines at the energies given in Table 2. The resulting χ^2_ν is 1.24 for 921 dof. There is no evidence for the presence of the 0.74 keV Fe XVII and 0.77 keV O VIII/Fe XVIII features with 95% confidence upper limits on the EW of 14 and 16 eV, respectively. The EW of the 0.96 keV Fe XX/Ni XX feature of 14±3 eV is similar to the values seen by the OGS and SSS of 12±5 and 30±10 eV, respectively. However, the EW of the 1.12 keV line of 24±3 eV is larger than measured by both the OGS (5±2 eV) and SSS (10±3 eV). We caution that the narrow-line fit accounts for only about half the line flux observed, suggesting the presence of other emission features in this energy range.

3. Discussion

Models for the continua of many bright LMXRB sources often require at least two components, e.g. a blackbody and a cut-off power-law model (White et al. 1988). A blackbody component is not required to fit the LECS

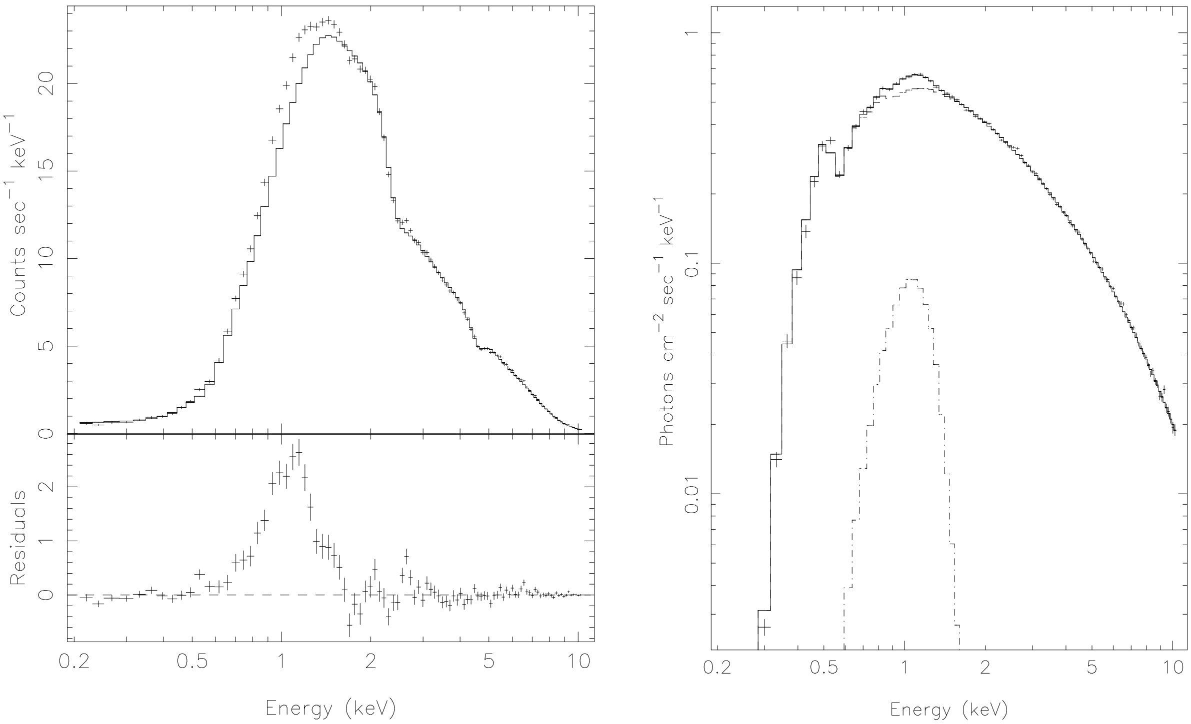

Fig. 1. The observed LECS spectrum together with the best-fit cut-off power-law model with the normalization of the 1.02 keV emission feature set to zero (upper left panel). The lower left panel shows the residuals. The right panel shows the inferred photon spectrum and the model prediction including the 1.02 keV feature

Table 2. A comparison of LECS and *Einstein* line energies and equivalent widths[a]

Line energy (keV)	Line identification	EW OGS (eV)	EW SSS (eV)	EW LECS (eV)
0.74	Fe XVII	4 ± 2	10 ± 3	<14
0.77	O VIII/Fe XVIII	6 ± 3	10 ± 3	<16
0.96	Fe XX/Ni XX	12 ± 5	30 ± 10	14 ± 3
1.12	Fe XVII/ Fe XXIII–XXIV	5 ± 2	10 ± 3	24 ± 3

[a] The OGS and SSS results are taken from Vrtilek et al. (1988) as are the line energies and identifications.

spectrum. The absence of the blackbody component when Cyg X-2 is on the upper left part of its horizontal branch of the *Z* has been noted by Kuulkers et al. (1995). The blackbody component appears to be present on all other parts of the *Z* (Hasinger et al. 1990; Kuulkers et al. 1995).

Although the timing properties can in principle be used to determine the position of Cyg X-2 in its *Z* variability pattern, there are insufficient counts in the LECS data to uniquely determine it. The intensity of Cyg X-2 is normally a factor of ~2 higher (e.g. Hasinger et al. 1990; Kuulkers et al. 1995) than during the *BeppoSAX* observation. Such low intensities are only reached during the so-called "low intensity" states of Cyg X-2 (Kuulkers et al. 1996). Inspection of the *Rossi* X-ray Timing Explorer All Sky Monitor (ASM) light curves (Wijnands et al. 1996) indicates that the *BeppoSAX* observation occured 5–10 days before Cyg X-2 entered a probable low intensity state, suggesting that the source was transitioning from a medium to a low intensity state. We note that a similar transition may have been seen by Vrtilek et al. (1986; their "medium state B"). Vrtilek et al. (1986) fit the 1–20 keV *Einstein* Monitor Proportional Counter (MPC) spectra obtained during this state with a thermal bremsstrahlung model of kT ~7.0–8.7 keV and N_H ~2.3–3.5×10^{21} H atoms cm^{-2}. A comparison with the best-fit parameters obtained when the same model is fit to the 1–10 keV LECS spectrum of kT~9.2 keV and N_H~3.5×10^{21} cm^{-2} indicates that the spectral shape was similar on both occasions.

The presence of excess emission near 1.0 keV was first suggested following a rocket flight in 1971 (Bleeker et al. 1972). As well as the OGS and SSS results reported in Vrtilek et al. (1986, 1988; see also Kallman et al. 1989 and Smale et al. 1994), Branduardi-Raymont et al. (1984) using the *Ariel V* Experiment C, Chiappetti et al. (1990) using the EXOSAT Channel Multiplier Array, Lum et al. (1992) using the *Einstein* Focal Plane Crystal Spectrometer, Smale et al. (1993) using the Broad Band X-ray Telescope and Smale et al. (1994) using the *ASCA* Solid State Imaging Spectrometer, all report evidence for excess emis-

sion near 1 keV. These reports indicate that the strength of the excess emission varies from observation to observation. No excess emission near 1 keV was reported by Pravdo (1983), Hirano et al. (1984), and Predehl & Schmitt (1995) using lower energy resolution data obtained with the HEAO 1 A2, *Hakucho* proportional counter, and *ROSAT* Position Sensitive Proportional Counter instruments, respectively.

Line emission at energies near 1 keV is not unique to Cyg X-2. Similar features have been observed in other LMXRB, e.g. in the *Z* source Sco X-1 (see Vrtilek et al. 1991), and in the accreting pulsars Her X-1 (McCray et al. 1982; Oosterbroek et al. 1997) and 4U 1626−67 (Angelini et al. 1995; Owens et al. 1997). The feature is most probably due to a combination of unresolved Fe L-shell and Ne K-shell line emission (Chiappetti et al. 1990; Vrtilek et al. 1991; Lum et al. 1992; Smale et al. 1993, 1994; Angelini et al. 1995). Vrtilek et al. (1988) modeled the ~1 keV excess emission seen from Cyg X-2 with *Einstein* using four narrow emission lines which they identify with Fe XVII, O VIII/Fe XVII, Fe XX/Ni XX and Fe XVII/Fe XXII–XXIV features (see also Kallman et al. 1989). The LECS spectrum was fit with the same model, and we find that the Fe XVII and O VIII/Fe XVII features are not present (although the 95% confidence upper limits are consistent with the *Einstein* detections), the EW of the Fe XX/Ni XX feature is similar to the values reported in Vrtilek et al. (1988), and the EW of the Fe XVII/Fe XXII–XXIV feature is significantly greater (see Table 2). These differences imply that the shape of the feature, as well as its overall EW, varies from observation to observation. It is notable that the narrow line model only accounts for about half the line flux of the excess emission as seen with the LECS, implying the presence of other features near 1 keV.

The Fe-L emission may be produced by photoionization of the surface of the accretion disk and the accretion disk corona by the strong X-ray continuum flux emanating from the central regions (see e.g. Kallman et al. 1989; Raymond 1993). Recent calculations by Kallman (1995) show that the ratio of the equivalent widths of the Fe-L and Fe-K lines should be close to unity for Cyg X-2. Our measurements indicate that this ratio is $\lesssim$1.2 (3σ), consistent with these calculations.

The strength of the low-energy feature is expected to be dependent on the temperature and density of the illuminated corona (e.g. Lidahl 1990; Kallman 1995), and probably indirectly on the mass accretion rate onto the neutron star which probably influences the X-ray continuum and shape of the inner accretion disk. Since these parameters can vary from observation to observation, it is not surprising that the strength and shape of the excess emission near 1 keV is variable.

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